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An mm-Wave CMOS I-Q Subharmonic Resistive Mixer for Wideband Zero-IF Receivers

Dristy Parveg, Mikko Varonen, Amirreza Safaripour, Pekka Kangaslahti, Mikko Kantanen, Tero Tikka, Todd Gaier, Kari A. I. Halonen, and Ali Hajimiri

Abstract—In this letter, we propose a novel wideband subharmonically pumped fully differential I-Q resistive mixer architecture which eliminates the necessity of on-chip DC-blocking capacitors to integrate IF amplifiers. The proposed differential subharmonic mixer topology is verified by presenting a CMOS millimeter-wave monolithic integrated circuit (MMIC) which includes the mixer and two on-chip differential IF amplifiers at the mixer's I- and Q-channels. The 3-dB IF frequency bandwidth is measured from 0.01 to 5 GHz with a peak conversion gain of -2 dB and an image rejection ratio (IRR) of more than 25 dB over the IF frequency range. The proposed mixer covers the input signal (RF) frequency from 170 GHz to 185 GHz. The mixer has also been tested with an on-chip voltage-controlled oscillator (VCO) and shows -4.7 dB conversion gain with a 3-dB IF bandwidth from 0.01 to 4.5 GHz.

Index Terms—CMOS, differential mixer, I-Q, IF integration, image-rejection, mm-wave, mixer, MMIC, passive mixer, receiver, resistive mixer, subharmonic, quadrature.

I. INTRODUCTION

CMOS technology has shown its potentiality in designing RF front-end circuits at mm-wave frequencies ranging from earth remote sensing receivers [1]–[3], to mm-wave communications [4]–[7]. For applications requiring multi-chip receiver modules, subharmonic mixers are preferred to fundamental mixers because the required local oscillator (LO) signal is half in frequency and therefore easier to distribute [8]. In addition to that subharmonic mixers reduce the LO-to-RF leakage. However, it should be noted that the phase noise

requirement for the LO is same as would be for the systems using a fundamental mixer and a frequency doubler.

At millimeter-waves, relatively low conversion loss or even gain can be achieved with active mixer topologies. Although passive mixers suffer from relatively high conversion loss, the benefit of using a passive mixer is the low $1/f$ noise performance and better linearity [9]. Since passive mixers do not consume any DC power, an amplifier stage can be added before RF down conversion to compensate for the conversion loss without an excessive increase in the power consumption of the receiver. Furthermore, resistive mixers can be designed for very wideband IF, RF and LO performances [10][11].

In [2], a wideband subharmonic resistive mixer including on-chip IF amplifiers with a record conversion gain was presented. However, the on-chip DC-blocking capacitors used for integrating the IF amplifiers limited the circuit performance at lower IF frequencies. To overcome this issue, in this paper, we propose a novel subharmonically pumped fully differential I-Q resistive mixer architecture which is suitable for wideband zero-IF receivers. The architecture eliminates the necessity of on-chip DC-blocking capacitors to integrate the IF amplifiers, therefore, the IF bandwidth is dependent on the IF amplifier. The proposed circuit topology is verified by presenting a compact CMOS I-Q subharmonic resistive mixer along with two differential IF amplifiers.

II. MIXER DESIGN

A simplified block diagram of the proposed subharmonically pumped fully differential I-Q resistive mixer architecture is shown in Fig. 1(a). The mixer employs two singly-balanced unit-cell mixers. To integrate the IF amplifiers without the need of on-chip DC blocking capacitors a novel unit mixer topology shown in Fig. 1(b) was developed.

The differential LO-signal at half of the RF frequency is fed to the gates of the transistors utilizing on-chip spiral balun. The LO distribution network and the transistor sizing is the same to our previously reported passive subharmonic I-Q mixer in [2].

A transformer is used to convert the single-ended RF-signal that is fed from one of the ports of on-chip Lange coupler to a differential mode and match the drains of the transistors at RF frequencies. The center tap of the transformer is acting as a virtual ground for the IF signal. An RF short-circuiting capacitor C_3 is also connected to the center tap of the transformer.

Quarter wavelength (at LO frequency) open shunt stubs are used at the drains to short the LO frequencies. The open

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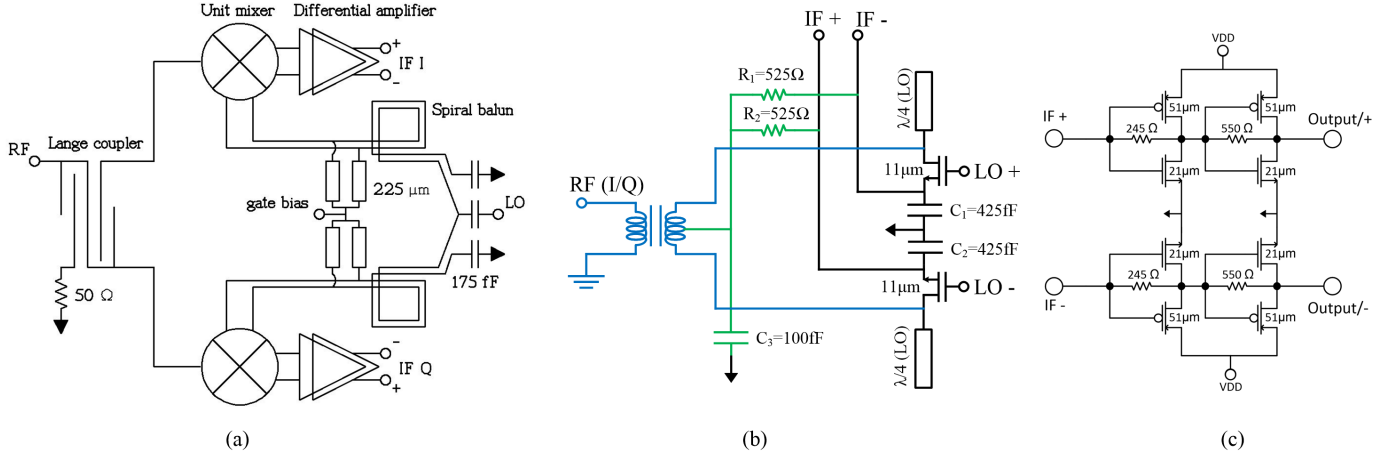


Fig. 1. (a) A simplified schematic of the proposed subharmonically pumped fully differential I-Q mixer architecture. (b) Circuit diagram of the proposed unit mixer. (c) Circuit diagram of the implemented two-stage differential amplifier for IF amplification.

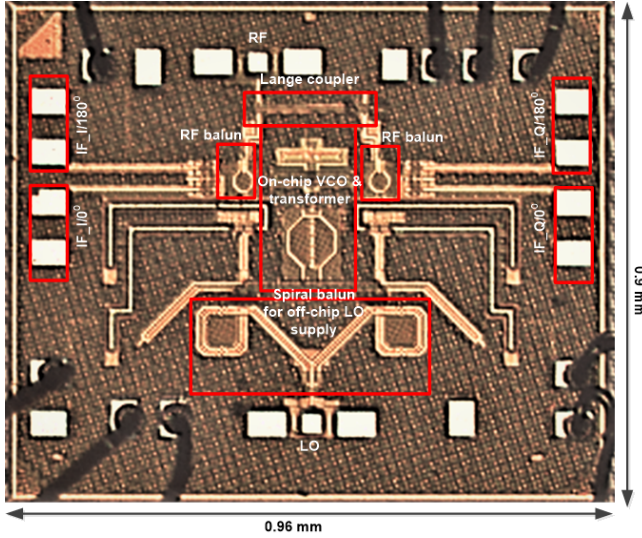


Fig. 2. Micrograph of the realized subharmonically pumped CMOS differential I-Q mixer with integrated VCO and IF amplifiers.

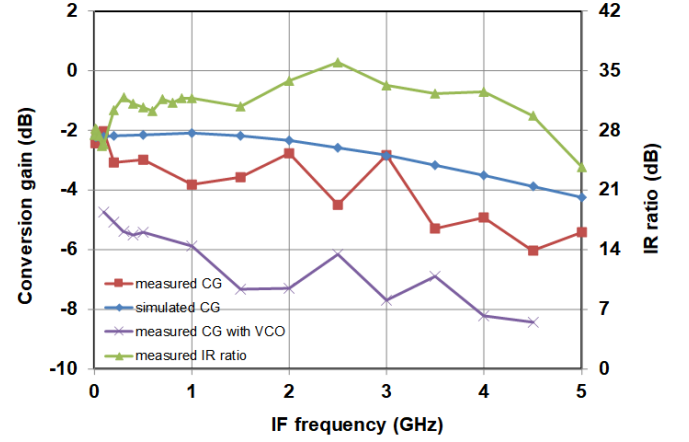


Fig. 3. Measured CG and IRR and simulated CG for a fixed LO frequency of 85 GHz while the RF is swept from 170.01 GHz to 175 GHz when the mixer is driven with an external LO supply. The figure also includes a measured CG at a fixed LO-frequency of 87.9 GHz while the RF is swept from 175.9 GHz to 180.3 GHz when the mixer was driven with the integrated VCO.

shunt stub is the half wavelength at RF frequency, therefore presenting a high impedance at RF frequency. IF is extracted from the sources of the transistors. Small-valued capacitors (C_1 and C_2) are used to connect the sources of the transistors. This connection is a short-circuit at LO and RF frequencies but open-circuit at IF frequencies. Because the bias voltage of the IF amplifier is connected to the sources of the unit mixer, therefore, large valued resistors (R_1 and R_2) are connected to the drains of the transistor through the center tap of the transformer in order to ensure that the drain and source of the unit mixers stay at the same potential.

III. MIXER IMPLEMENTATION

In order to validate the proposed topology, we have designed a subharmonic I-Q differential resistive mixer with two differential IF amplifiers at the mixer's I- and Q-channels. The center frequency for the RF is at 170 GHz, and the LO was at 85 GHz. The differential IF-signals produced from the

mixers are amplified by the differential IF amplifiers capable of producing a gain of 16.5 dB with a 3-dB bandwidth from DC to 5 GHz. The differential amplifier is designed by connecting two two-stage cascaded resistive feedback inverters in parallel as shown in Fig. 1(c).

A free-running voltage controlled oscillator (VCO) operating around 85 GHz as reported in [1] is also integrated into the mixer circuit as an option of on-chip LO supply. A differential cross-coupled LC oscillator with varactor tuning is used as the VCO to generate the required differential on-chip LO signals and fed to the mixer through a 1:1 on-chip transformer. The VCO is followed by two ac-coupled cascode buffer stages with 20- μm and 40- μm wide transistors, respectively, before feeding the transformer [1].

All the transmission lines including the Lange coupler are realized in the microstrip environment and modeled through an electromagnetic (EM) simulator. The transformers, spiral baluns, and probing pads are characterized by EM simulations. The transistors are modeled by R/C parasitic extraction and

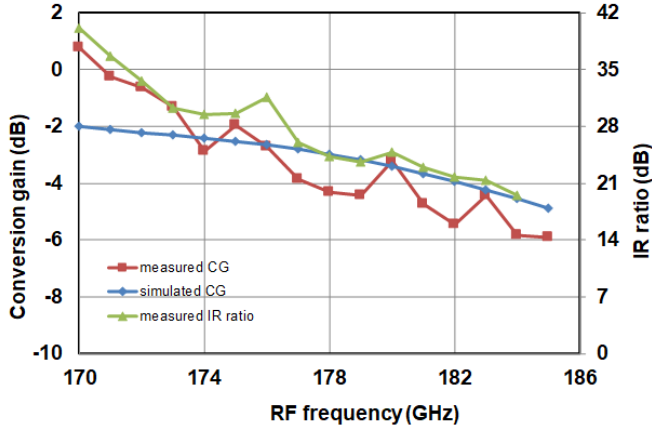


Fig. 4. Measured CG and IRR and simulated CG for a fixed IF-frequency of 1 GHz while the LO (84.5 to 92 GHz) and RF (170 to 185 GHz) were swept.

EM model for the access connections [12]. The chip was fabricated in a 32-nm Silicon-on-insulator (SOI) CMOS technology and consumes a total silicon area of 0.86 mm². A micrograph of the chip is shown in Fig. 2.

IV. MIXER PERFORMANCE

A. Measurement with External LO supply

On-wafer measurements were carried out to observe the performance of the designed mixer. The LO-signal was provided from a W-band source and the RF-signal was obtained from a G-band source. The LO-, RF-, and IF-signal paths were calibrated up-to-the probe tips. The output IF-signal spectrum was measured with a spectrum analyzer. The phase and amplitude balance were measured with an Oscilloscope to calculate the IRR of the mixer. The resistive mixer itself does not consume any current as there is no supply voltage required. However, the IF amplifiers consume 100 mA current at 1.2-V supply. For optimum second harmonic mixing, the gate-to-source voltage of the resistive mixers was set to 0.17 volts. The actual applied DC voltage to the gates was 0.8 V because the DC potential to the source and the drain were 0.63 V (from the IF amplifier). In all measurements, the LO power was fixed at +4-dBm which was found to be enough for optimum mixing performance (see also [2]).

The down-converted conversion gain (CG) was measured from 10 MHz to 5 GHz when the LO was fixed at 85 GHz, and the RF was swept from 170.01 GHz to 175 GHz. For a 3-dB IF bandwidth from DC to 5 GHz, a CG of -2 to -5.5 dB was measured and for this frequency range, the simulations compare well with the measurements as shown in Fig. 3. To measure the RF frequency performance, both the LO and RF frequency were swept while keeping the IF-frequency constant at 1 GHz. Fig. 4 shows the LO-frequency sweep from 84.5 GHz to 92 GHz when the RF was swept from 170 GHz to 185 GHz. The simulated 3-dB bandwidth is from 160 to 185 GHz and the measured and simulated result shows a reasonable fit over a wide frequency range. Figure 3 and 4 also include the measured IRR of the designed differential mixer. A better

TABLE I
STATE-OF-THE-ART PERFORMANCE OF MM-WAVE I-Q SUBHARMONIC PASSIVE MIXERS

Ref.	Topology	Process	RF (GHz)	CG (dB)	IF (GHz)	PLO (dBm)	IRR (dB)	1-dB ICP (dBm)	PDC (mW)
[13]	Subharmonic passive I-Q mixer	90 nm CMOS	50-62	-15	1-3	4	>20	-8**	0
[8]	Subharmonic passive I-Q mixer	35 nm InP HEMT	180	-20	0.01-1	3	>20	-	0
[14]	LNA+Subharmonic passive differential I-Q mixer +IF amp +VCO	130 nm CMOS	24	12.5	0.03-0.44	-	>20	-17#	166.4
[2]	Subharmonic passive I-Q mixer +IF amp	32 nm SOI CMOS	158-182	8 [†]	1-10	4	>20	-1*	74
This work	Subharmonic passive I-Q differential mixer +IF amp	32 nm SOI CMOS	170-186	-2 [†]	0.01-5	4	>20	+1*	120
This work	Subharmonic passive I-Q differential mixer +IF amp +VCO	32 nm SOI CMOS	170-180	-4.7 [†]	0.01-4.5	-	-	-	175

*Simulated [†]Stand-alone mixer has a simulated CG of -20 dB [‡]Stand-alone mixer has a simulated CG of -23 dB **Up-conversion mode #A 8-dB LNA is placed before the mixer

than 25 dB IRR is measured over a wide IF and RF frequency range.

The simulated 1-dB input compression point of the circuit (mixer and the IF amplifier) is +1 dBm. The simulated double-sideband noise figure (NF) of the circuit is around 24.5 dB from 165 to 185 GHz. This means that a noise figure of below 10 dB is expected if an RF amplifier presented in [3] having a 25-dB gain and 9-dB noise figure is utilized before the mixer.

B. Measurement with Internal LO-supply

The mixer was tested also with the on-chip VCO. The VCO consumes a DC power of 55 mW and shows a tuning range from 86.5 to 88 GHz. The down-converted IF-frequency range was measured from 0.01 to 4.5 GHz. Fig. 3 shows CG from -4.5 dB to -8.5 dB when the LO was tuned at 87.9 GHz, and the RF was swept from 175.9 GHz to 180.3 GHz. Since the VCO is operating as a free-running LO source the IRR of the mixer was not tested with the internal LO-supply. From Figure 3, we can see that the mixer has lower conversion gain and IF bandwidth which indicates a lower available LO power from the integrated VCO.

V. CONCLUSION

In this letter, we have proposed a novel wideband differential subharmonic I-Q resistive mixer topology which enables the IF amplifier to be connected to the mixer core without a DC blocking capacitor. Furthermore, we have validated the proposed circuit concept by designing a 170 GHz differential subharmonic I-Q resistive mixer with the integrated IF amplifiers and VCO in a CMOS technology. The state-of-the-art results published for mm-wave subharmonic I-Q passive mixers are shown in Table I. Compared to the mixer in [2] having limited IF operation below 1 GHz, the mixer presented in this letter achieves at least a 0.01 to 5 GHz 3-dB IF bandwidth. To the best of authors' knowledge, this work presents the widest IF-bandwidth with high linearity for an I-Q subharmonic passive mixer suitable for zero-IF receivers.

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